



Optical Thin Film Modeling

Using FTG's FilmStar Software

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Optical Background



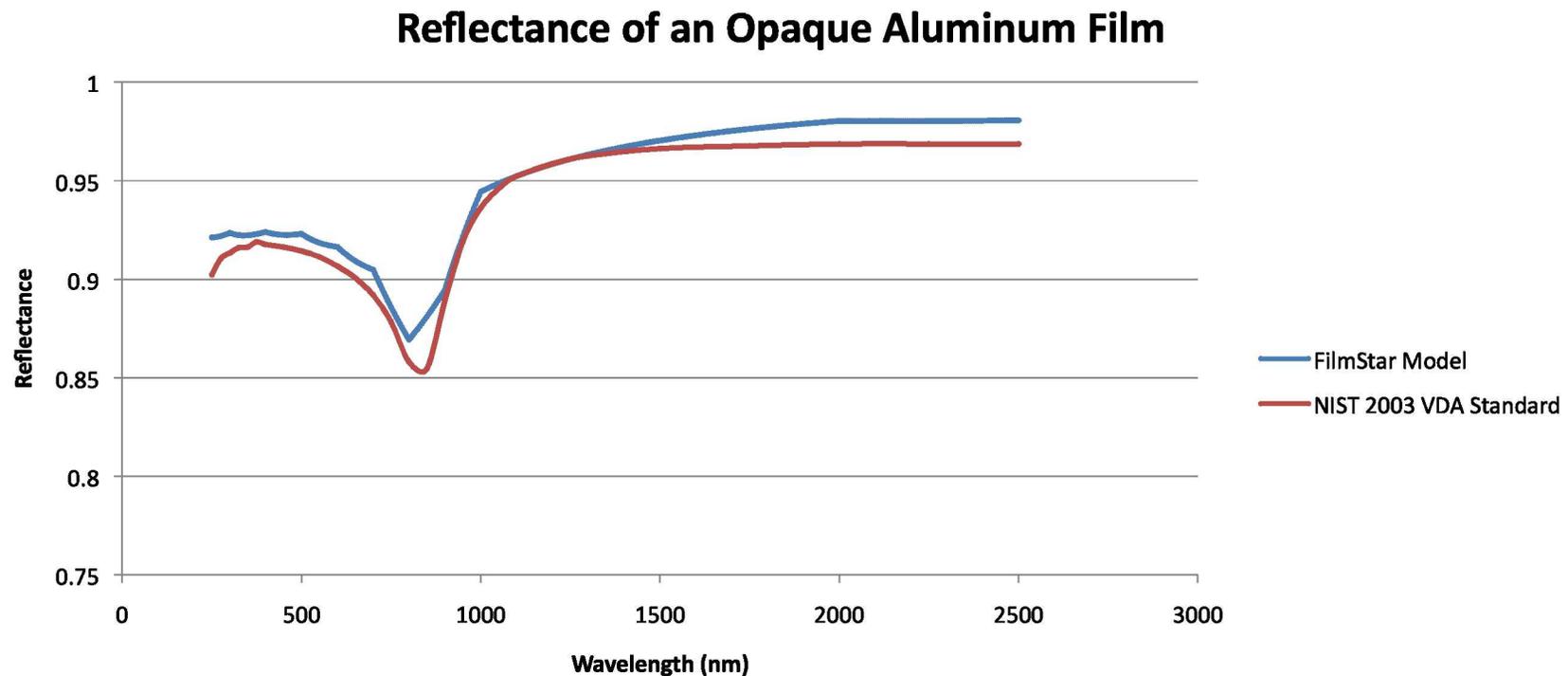
- Every material has basic optical properties that define its interaction with light
 - The index of refraction (n) and extinction coefficient (k) vary for the material as a function of the wavelength of the incident light.
- Also significant are the phase velocity and polarization of the incident light
- These inherent properties allow for the accurate modeling of light's behavior upon contact with a surface
 - Reflectance, Transmittance, Absorptance



Reflectance Curve of an Aluminum Mirror



- Comparison of modeled opaque Aluminum film (left) to NIST Standard for Vapor Deposited Aluminum (right)





Optical Background



- Reflectance is calculated by:

$$R = (N_{sub} - N_{med})^2 / (N_{sub} + N_{med})^2$$

- $N_{med} = 1$ for vacuum, ≈ 1 for air
- $N = n - ik$; complex when absorption is not negligible

- For glass (SiO_2), $n \approx 1.5$, $k \approx 0$ in the visible range
 - $R = .04$, or 4% at each interface
- For a lens, $\sim 8\%$ of incident light is lost
 - Imagine with complex multiple optic system!





Unwanted Reflectance



- By the time light reaches a sensor, consequential loss can occur.
- This has obvious negative effects on data gathering ability.
 - Less light received, less information to analyze
- Reflectance must be minimized in order to maximize throughput.
 - Or for mirrors, reflectance would ideally be maximized.
 - A similar technique is used.



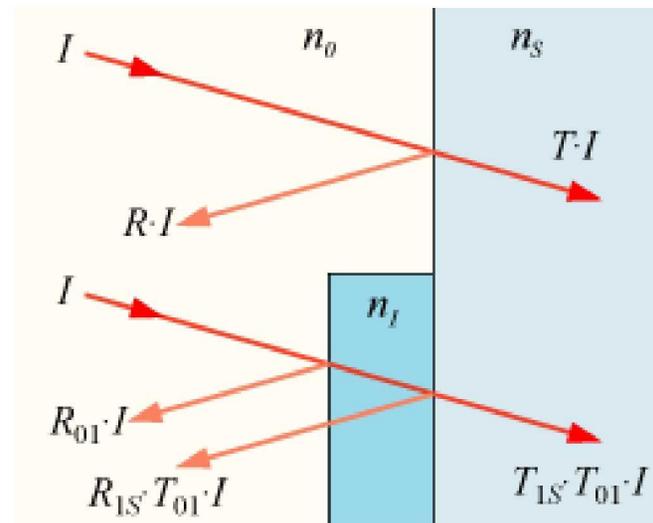
Optimization of Optical Behavior

- Thin films of materials with different optical properties can enhance the desired effects of a surface.
 - For a single layer anti-reflective coating:
 - $n_{medium} / n_{coating} = n_{coating} / n_{substrate}$
 - $n_{coating} = \sqrt{n_{substrate}}$, since $n_{medium} = 1$ for vacuum/air
 - Can be further optimized by adjusting layer thickness.
 - Even more so by introducing multiple layers.



Optimization of Optical Behavior

- Since glass has an index of refraction of $n = 1.52$, the ideal single layer AR coating has $n = 1.23$
 - Closest common film is MgF_2 , $n = 1.38$
 - Can reduce loss to $\sim 1\%$, a 4x improvement over bare surface.





Optimization of Optical Behavior

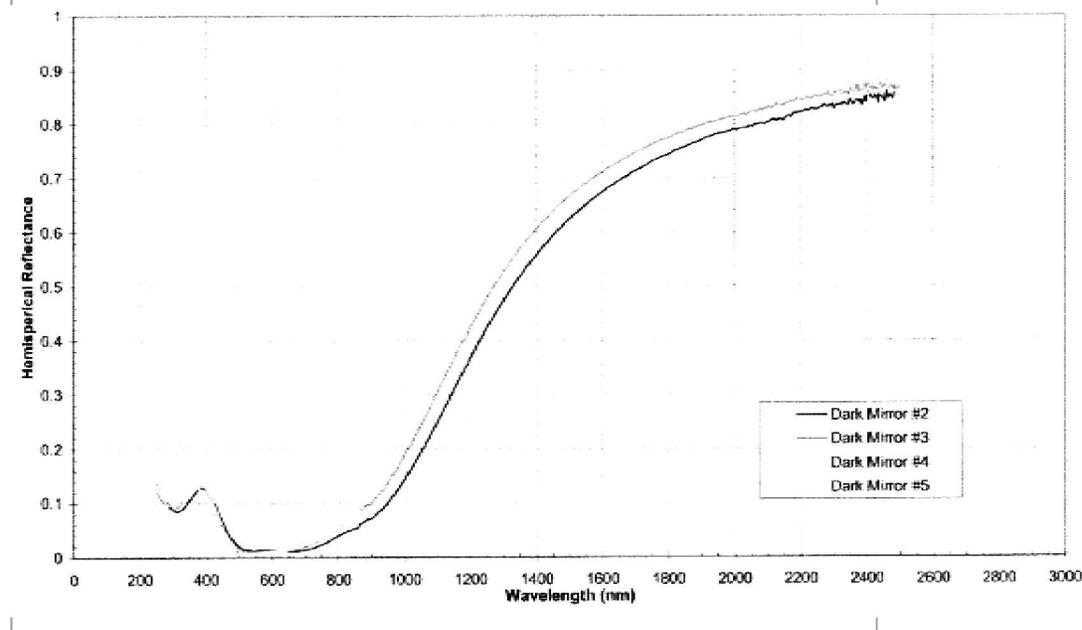
- Reflectance is actually optimized for a defined wavelength range
 - Since n , k are wavelength specific
- Principle is used to create coatings with a specific purpose
 - Most instruments focus on a specific wavelength range as well
 - e.g. – GSFC Dark Mirror Coating
 - Minimizes reflectance in the visible spectrum



Optimization of Optical Behavior



- Comparison of measured dark mirror (left) reflectance to modeled (right)
 - Standard layer thicknesses were obtained from George Harris of SGT, Inc./GSFC Code 546
 - From substrate: 100nm Al, 37-40 nm SiO, 5-7 nm Cr, 50-53 nm SiO
 - Thicknesses used in model:
 - From substrate: 100nm Al, 38nm SiO, 12nm Cr, 50nm SiO





Use of FilmStar Software

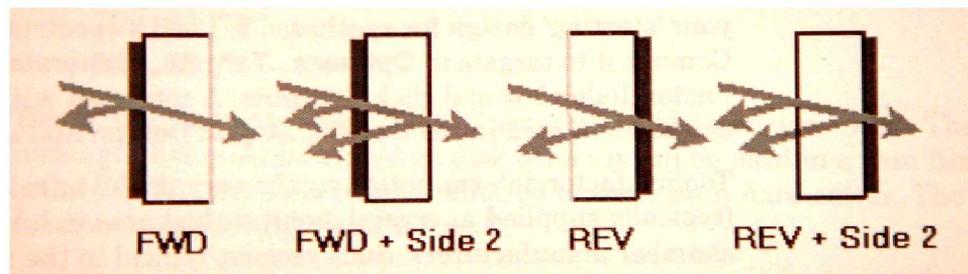
- FilmStar automates the calculation of reflectance (as well as transmittance, absorptance) for each wavelength
 - Uses data tables of n and k values for materials
 - Many common materials included, but still a need for others along with extended/updated tables of existing materials
- Task broken into two individual pieces of software
 - Index and Design
 - Index: creates/modifies data tables of n , k values
 - Design: the workhorse
 - Incorporates data tables, calculates behavior, and allows for modification and optimization.



Use of FilmStar: Design



- Allows for creation of custom coatings
 - First, a substrate is selected from materials
 - Can model bare substrate, one layer, or numerous layers
 - Each layer also to be selected from list of materials
 - Each set to custom thickness
- Automated calculation of optical behavior
 - Numerous options for results
 - %R, %T, %A, thickness relationship
 - Makes calculation using n , k values
 - Leaves option for what reflections to take into account





Use of FilmStar: Design



- Layer thickness is first input manually
- Design then has a function for optimization
 - User selects a target reflectance (or A, T)
 - Can be selected for any wavelength range
 - User also has option to select what layers the program is allowed to adjust
 - When inputs are set, the program calculates the coating thickness required to meet target
 - Further inputs for maximum change, and number of iterations to perform



Optimization of a Thin Film



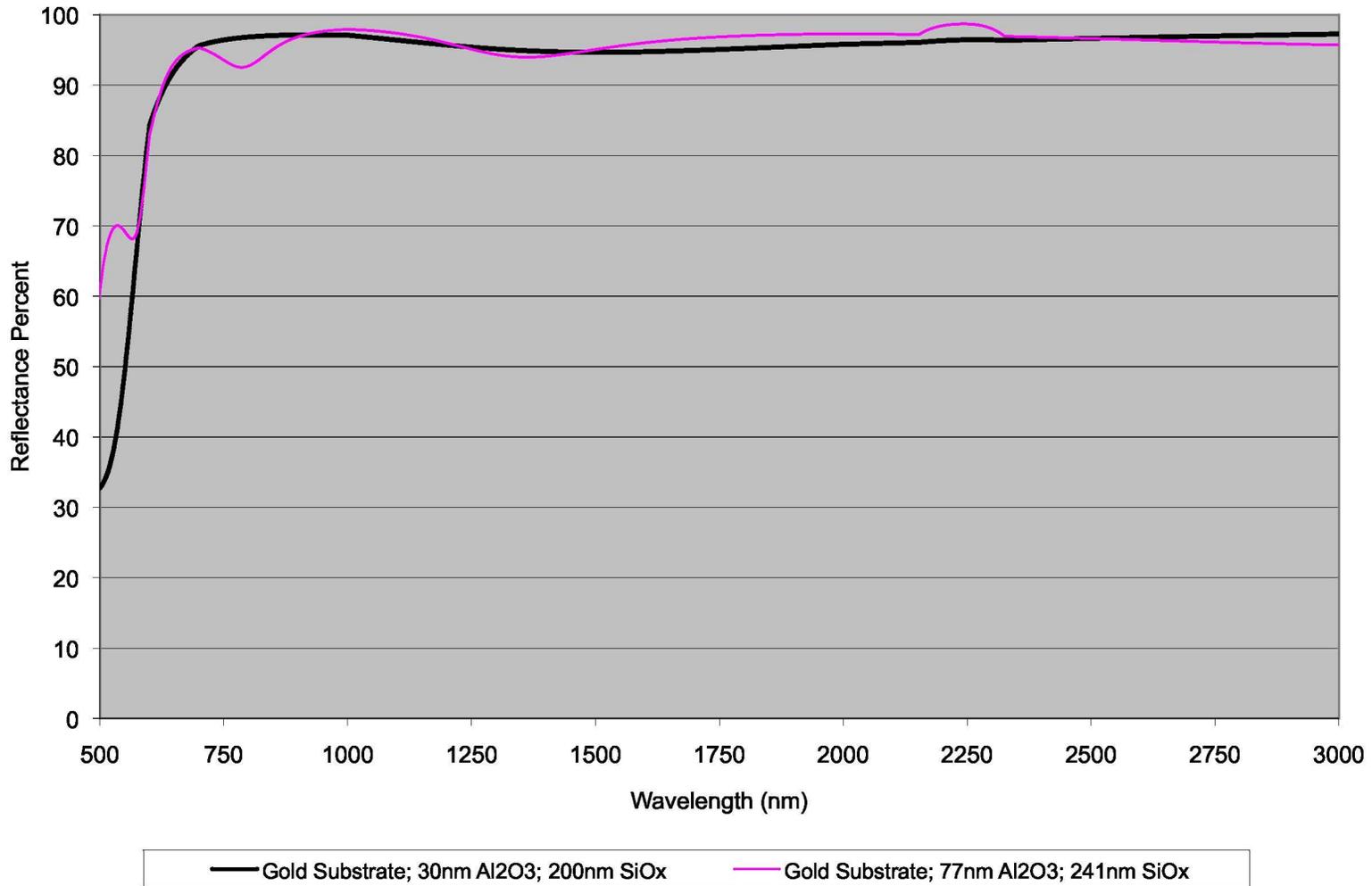
- The JWST Primary Mirror has a base gold film, with a protective coating
 - Gold is thick enough to be considered substrate
- Optimizing the surface coating
 - Exact “formula” unknown, but similar concept used
 - Started with formula of:
 - Gold Substrate; 30nm Al_2O_3 ; 200nm SiO_x
 - Optimization for $1\mu\text{m}$ led to formula of
 - Gold Substrate; 77nm Al_2O_3 ; 241nm SiO_x
 - Increase from 97.1 %R to 97.9 %R at $1\mu\text{m}$



Optimization of a Thin Film



Optimization of JWST Primary Mirror for Reflectance at 1 μ m

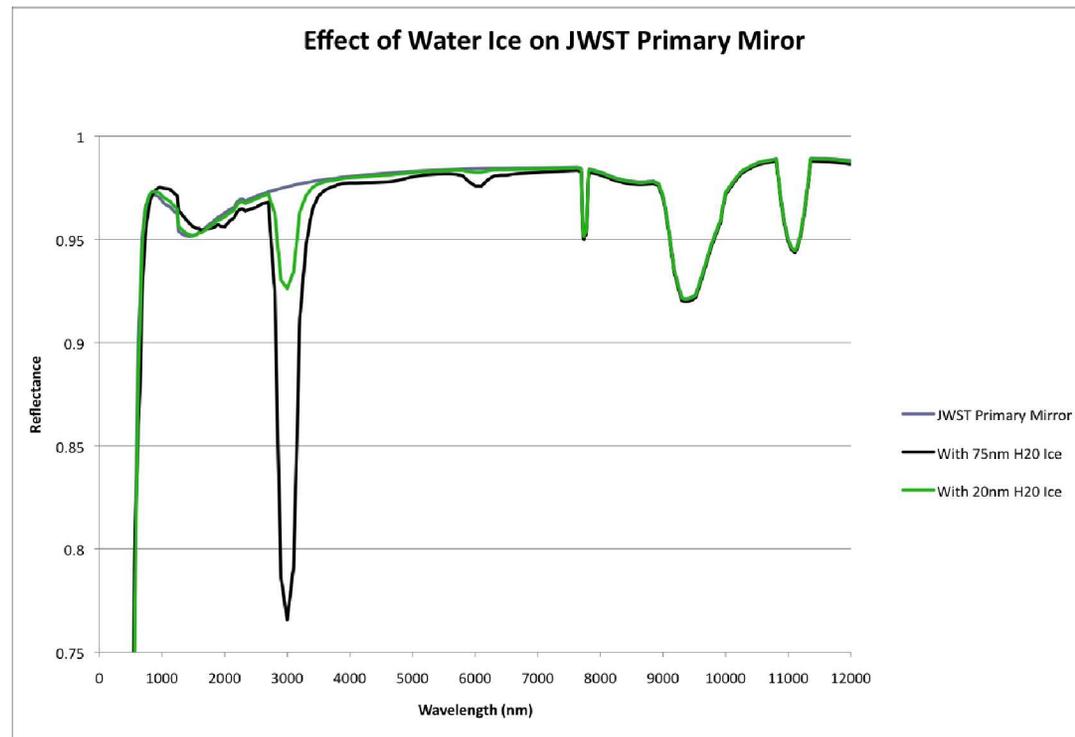




Contamination Modeling



- Extra advantage to thin film modeling
 - Can also model films that *shouldn't* be present
 - Determine worst case scenarios for materials expected to be present.
 - Need to assume a perfect thin film
 - e.g. – Water ice on JWST Primary mirror





Contamination Modeling



- Further capability of determining contamination details from observed data
 - Change in behavior of sensors can be related to a contamination film on it or in optics path
- Possible to classify the type of contamination, as well as thickness
 - Also possible to rule out a specific contaminant, or contamination in general



Contamination Modeling



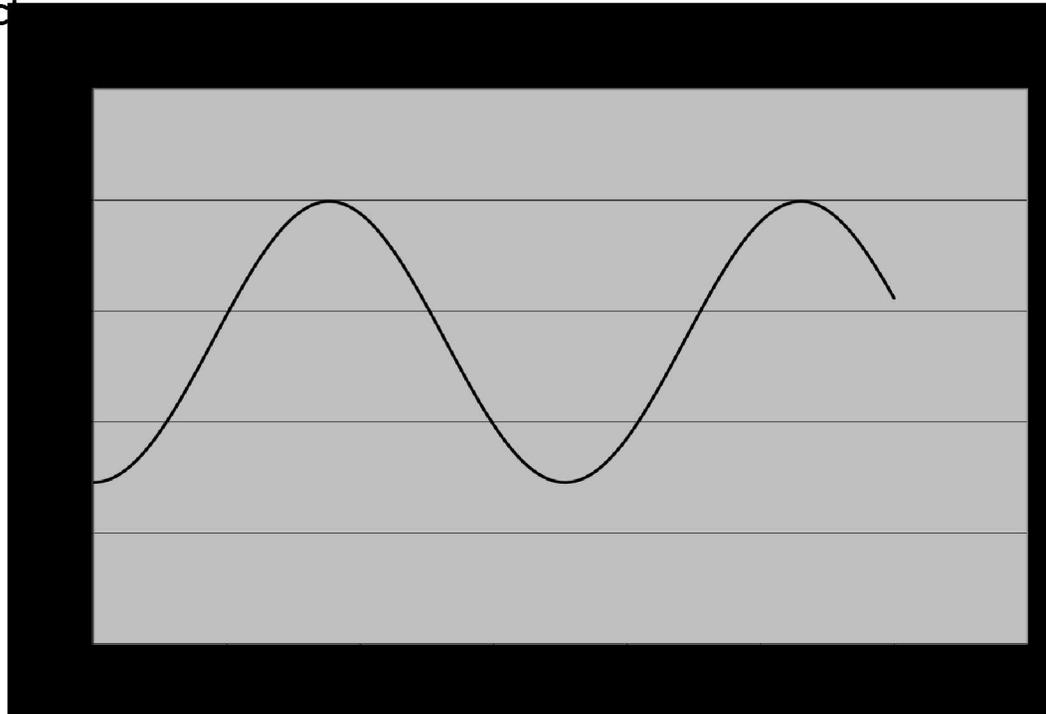
- SDO HMI Throughput Issue
 - Data showed an apparent dramatic signal difference between two CCDs at -90C in thermal vacuum cycling.
 - Possibly a significant change in throughput, or possibly data error
 - Film of water ice proposed by vendor, among other possible issues.
 - Exact CCD layering was unknown, but similar was modeled.
 - Created analysis of transmittance vs. thickness of water ice on a likely CCD substrate
 - At 473 nm, the peak wavelength of LED test source



Contamination Modeling



- Model showed a maximum increase of $\sim 3\%$ in transmittance with water ice on SiO_2 substrate (a likely CCD surface)
 - Significantly less change than what was observed.
 - Meant that water ice contamination was probably not the culprit
 - Limited data made it difficult to determine what was or was not the real cause
 - Also possible the effect was a data error in CCD efficiencies, not a real transmission effect





Limitations and Weakness



For Thin Film Modeling

- Need a complete and accurate model of the optical system
 - Inaccuracy in layers, materials, or thickness can greatly affect the outcome
 - Must interact with instrument teams to increase modeling strength
- Limited n , k data for some materials
 - Possibility for in house measuring



Limitations and Weakness *For Contamination Modeling*



- Must assume a perfect thin film
 - Contamination is often scattered and/or localized
 - Water condenses in spots converging outward
 - Think of frost on a car windshield
 - Possible interpretation as a weighted average of contamination's effect on the exposed optical area
- Must have an idea of what contaminants to expect
 - Some cases fairly predictable
 - Based on surface temperature for condensation



Future Capabilities



- Possibility for determining n , k values for less common materials, especially contaminants
 - Can be performed with existing spectroreflectometer instruments and extended FilmStar software: *Measure*
- Increased interaction with optical systems designers will vastly improve the modeling capability
 - Should also lead to better understanding of contamination limits, and improved contamination control plans